DYNAMIC POSITIONING CONFERENCE
October 17 – 18, 2000

SENSORS

Space Weather and the Ionosphere

Grant Marshall

Trimble Navigation Inc.

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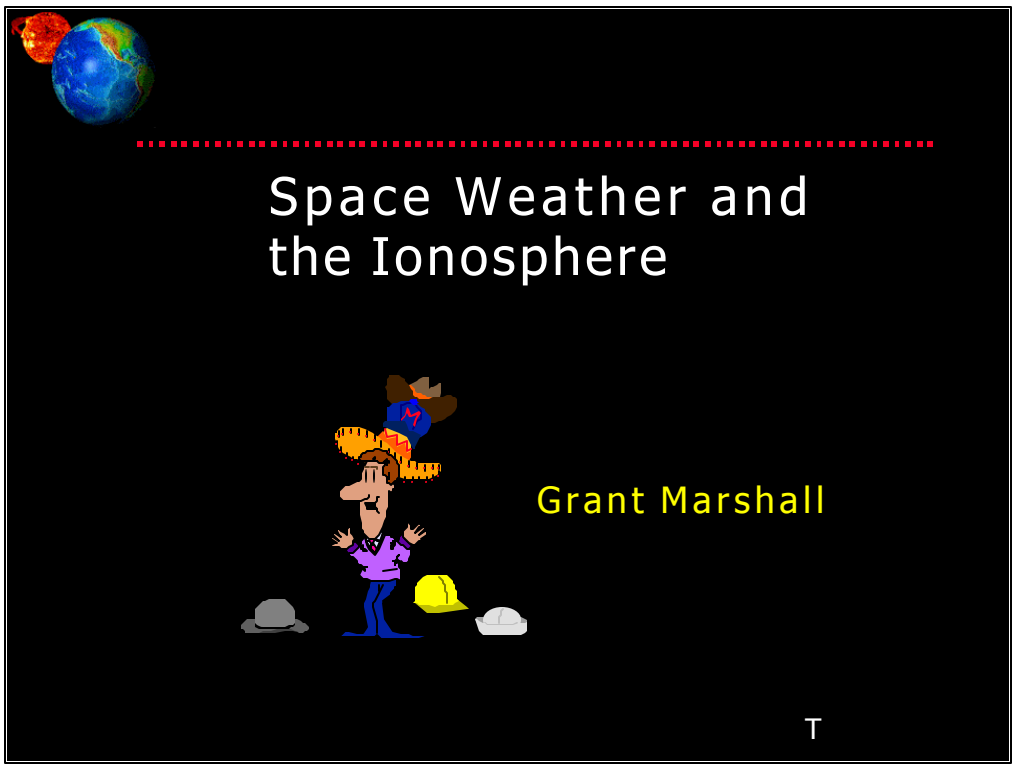
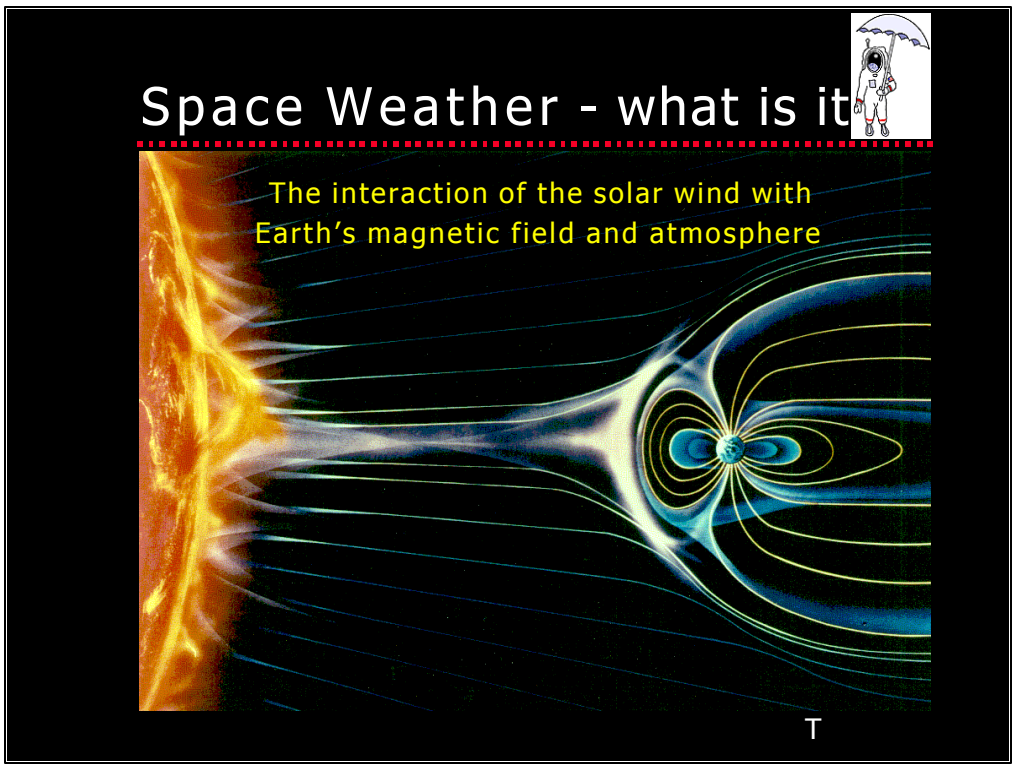


Many different professionals use GPS for their work. There are Land Surveyors, Cartographers, Geographers, Civil Engineers, Mining Engineers, Construction Engineers, and many others. The common thread that brings all these professions together is GPS. The more we learn about how our colleagues in other fields use GPS, the more we understand how to better use GPS in our own professions. So, as users of GPS, we wear many hats. For the next 45 minutes let's all put on our Space Weather Scientists hats and learn about how Space Weather affects GPS and the ways that we use it.

So what is Space Weather anyway? There is a hint on this slide in the upper left hand corner. It has something to do with the Sun and the Earth.

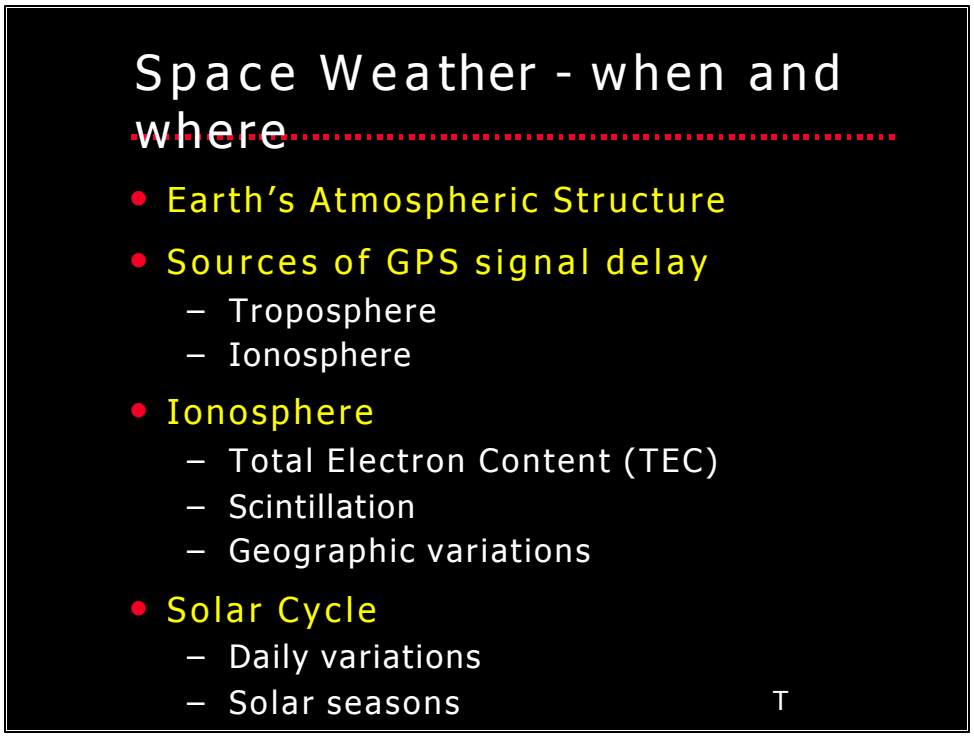


In fact, Space Weather has everything to do with the Sun. This picture really sums up the whole story very nicely. Space Weather is the interaction of the solar wind with Earth's magnetic field and atmosphere. The solar wind consists of particles and radiation from the sun that is streaming off the solar surface all the time. The solar wind reaches speeds of 500 kilometers per second. So, it is really howling out there. The solar wind, when it reaches the Earth, slams into the magnetic field and blows the magnetic field back into a long tail on the far side, away from the sun. Thus, whenever there are fluctuations in the solar wind, the Earth's magnetic field becomes disturbed - these events are sometimes referred to as magnetic storms. Radiation from the sun also enters Earth's upper atmosphere and creates the ionosphere, and we will discuss these interactions later in this presentation.

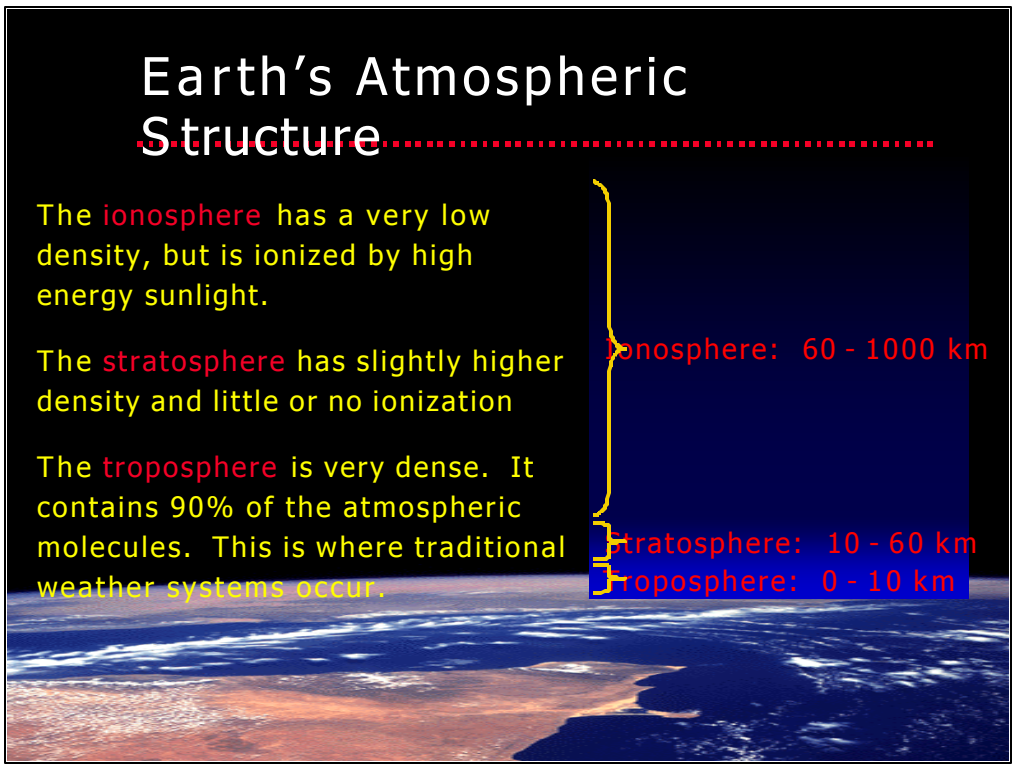
Space Weather - when and where

- Earth's Atmospheric Structure
- Sources of GPS signal
  - Troposphere
  - Ionosphere
- Ionosphere
  - Total Electron Content
  - Scintillation
  - Geographic
- Solar Cycle
  - Daily
  - Solar

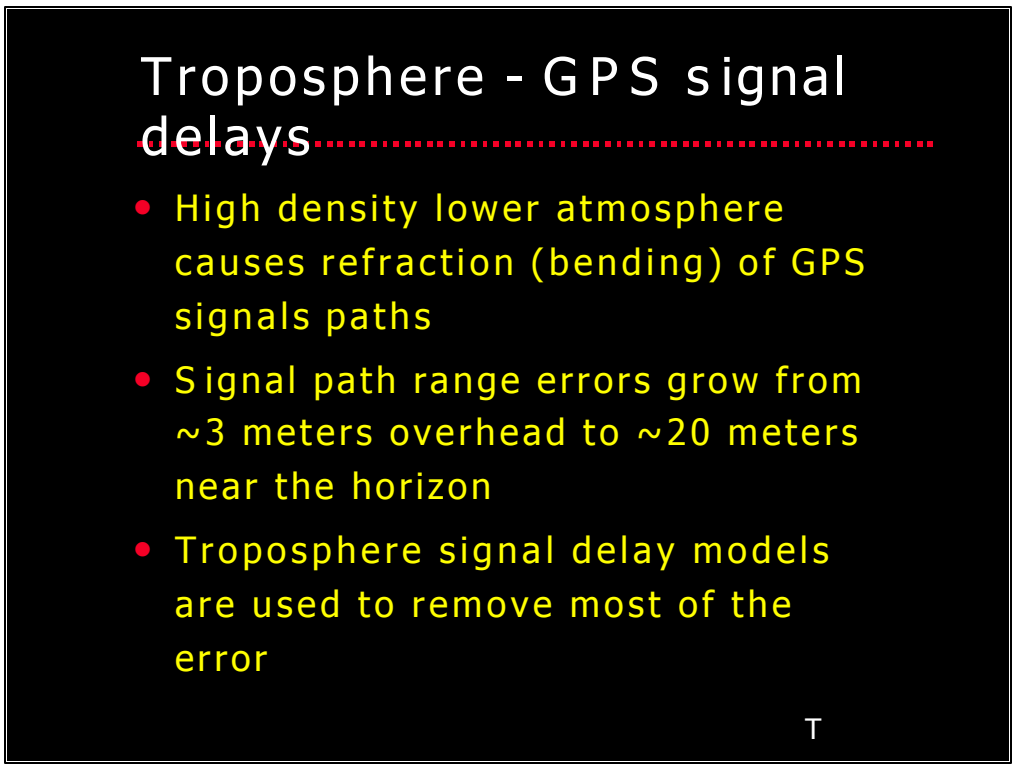
Here are some of the topics that we will be discussing today. We want to learn about when and where Space Weather occurs. First, we will want a simple understanding of the Earth's atmosphere. Next, we will be talking about sources of GPS signal delays in the atmosphere. The main sources of delay will come from the troposphere and the ionosphere and we will discuss both of these. We will then move on to look at the ionosphere in more detail. We will talk about how the ionosphere comes about and discuss the Total Electron Content. We will also talk about scintillation, which has become a real buzzword lately when discussing the ionosphere. We will see where the ionospheric disturbances are localized geographically. Since the ionosphere is directly connected with the sun's radiation, we will need to examine solar variations. We will examine the different time spans over which the sun's radiation output changes. We will look at daily variations, solar seasons, and also the 11-year solar cycle.



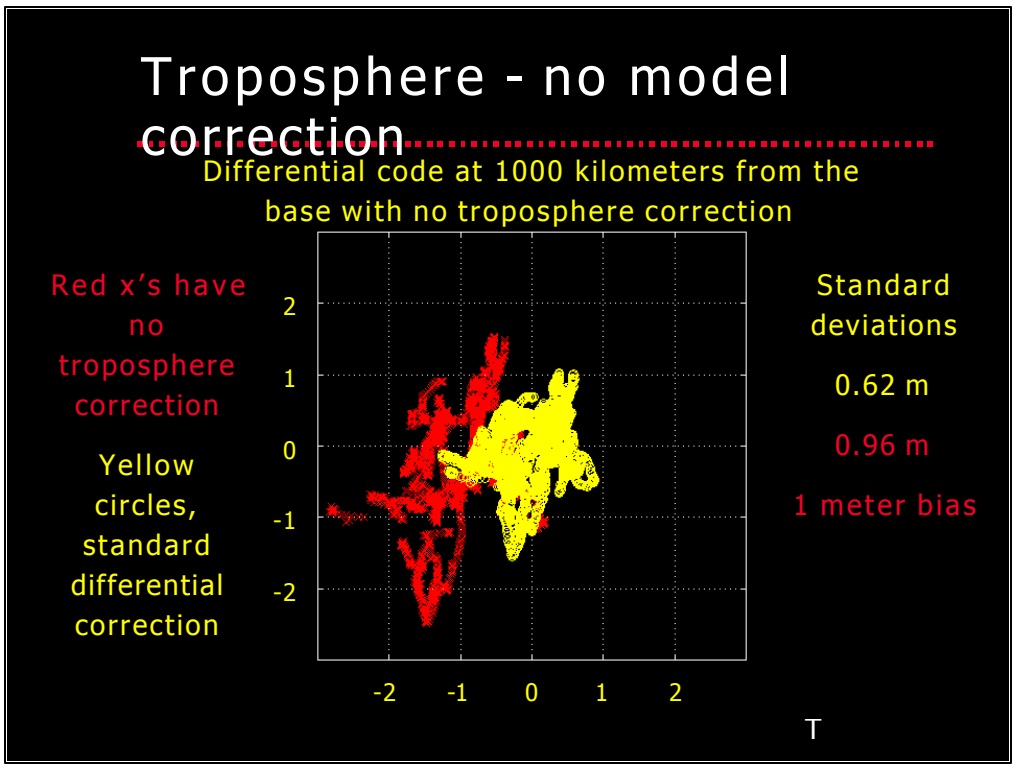
In the second half of the talk we will look at what we can do with our knowledge of Space Weather. We will search the Internet for information about Space Weather and the solar cycle. I will show you web sites that have educational materials about Space Weather and that list Space Weather alerts. We will look at a site where ionospheric scintillation is discussed in detail and a model is used to make scintillation predictions. And we see some sites where you can find Total Electron Content maps. Next we will talk about what Trimble is doing. We are focused on data collection and research and analysis. And finally we will look at what you can do. That is, we will see how you can change the way you work when you understand what Space Weather is all about.



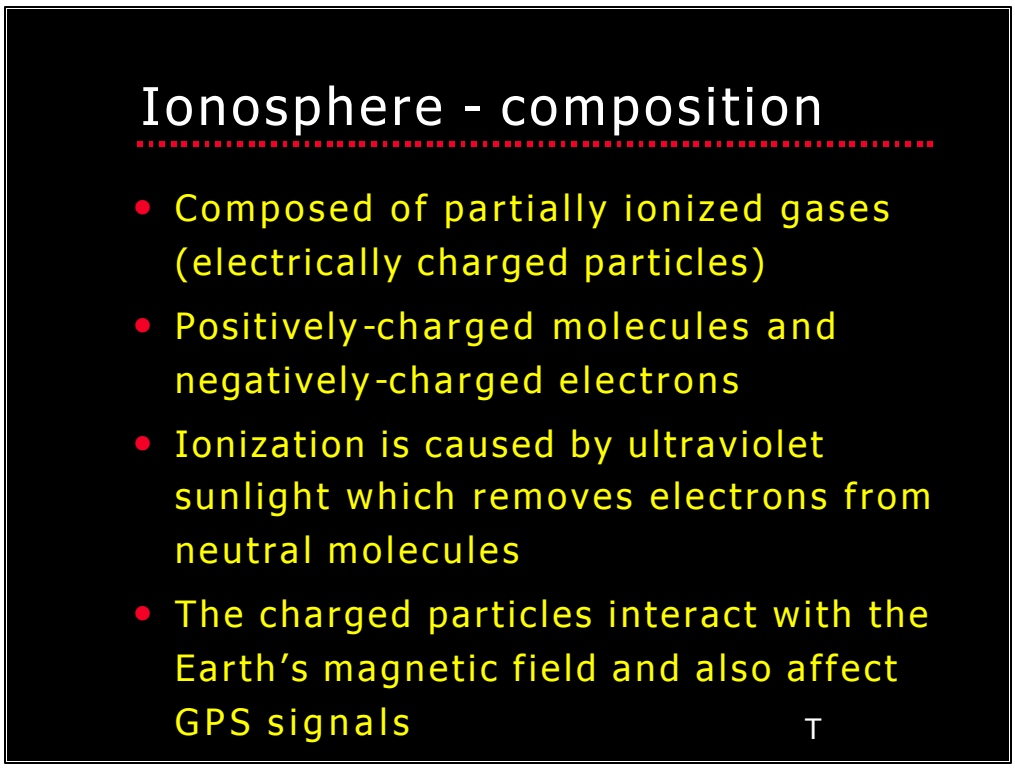
First, let's look at a simplified view of the Earth's atmospheric structure. The Earth's atmosphere can be divided into many layers, but for our discussion will just consider it to be composed of three layers. The troposphere is the lowest layer of the atmosphere. It stretches from the Earth's surface up to an altitude of about 10 kilometers. Ninety percent of the molecules in the atmosphere reside in the troposphere, so this layer is very dense. The troposphere is characterized by turbulent motions of the air masses and this is why storm systems and traditional weather occur there. Above the troposphere is the stratosphere, a lower density layer characterized calm layered air masses. The stratosphere lies between 10 and 60 kilometers altitude. Above the stratosphere is the ionosphere, which stretches from 60 to approximately 1000 kilometers altitude. This region of the atmosphere has very low density, but it is ionized. Sunlight causes the ionization and we will discuss what this means shortly.



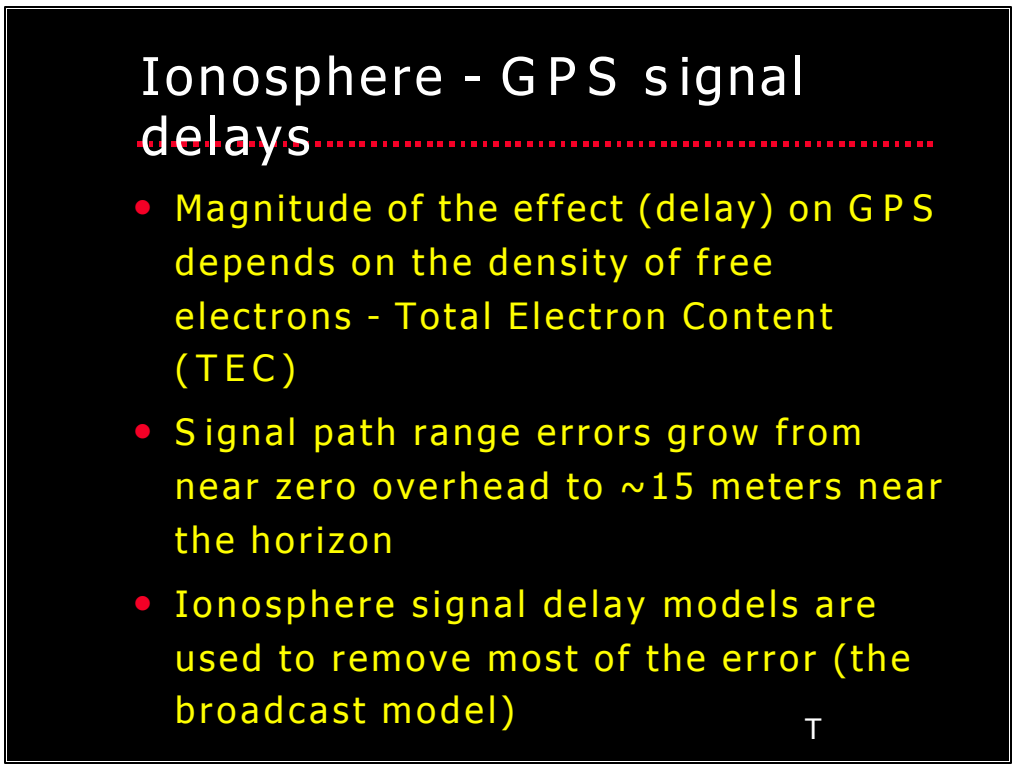
Let's look at how the troposphere affects GPS signals. The high-density troposphere causes refraction, or bending, of GPS signal paths. The range errors that we expect to see vary from about 3 meters overhead to about 20 meters near the horizon. The errors are largest near the horizon because the signals spend more time in the troposphere when they enter it at low elevation angles. The good news is that we have troposphere signal delay models. These models are used to remove most of the refraction error. Let's look at an example of troposphere-induced errors.



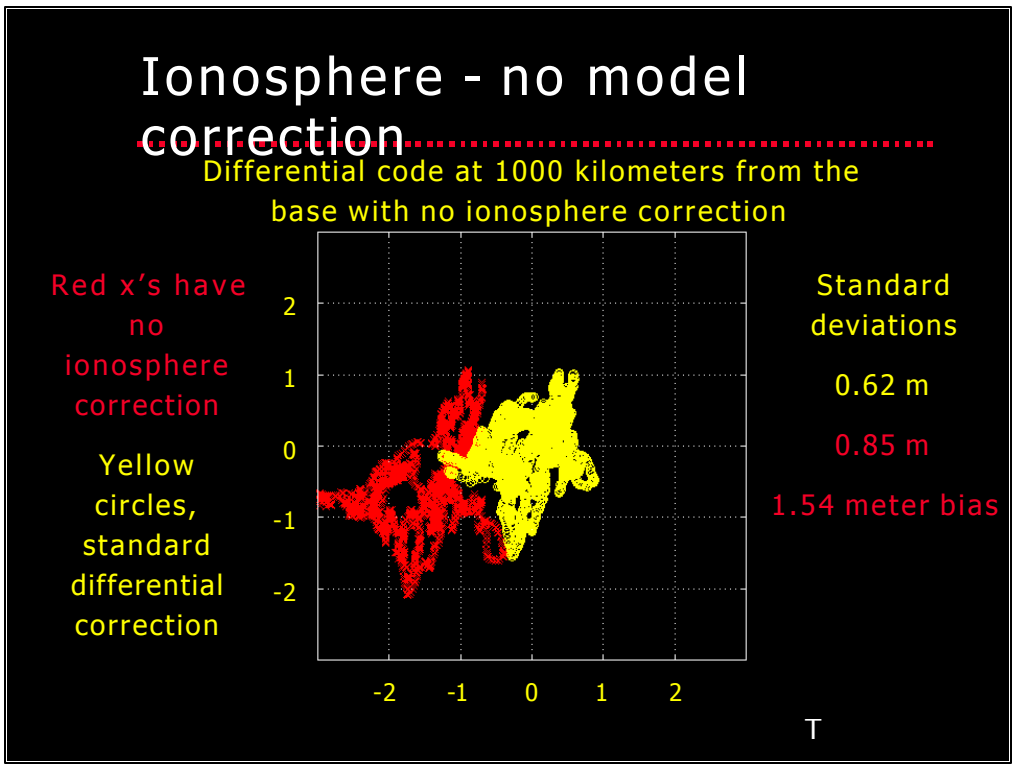
Here is a plot of differentially corrected code data. The data comes from two Trimble ProXR receivers that are 1000 kilometers apart. The yellow circles are from a standard differential correction like you would get from the Pathfinder Office Differential Correction software. The standard deviation is about 62 centimeters, well within the accuracy specification for the ProXR system (The specification is 50 centimeters plus 1 ppm. At 1000 km, 1 ppm equals 1 meter, so the specification for 1000 km is 1.5 meters.) The red x's show the differential correction with the troposphere model turned off. You can see that the scatter is much larger. The standard deviation increases by 50% to 96 centimeters. In addition to larger scatter, the red x's are also offset from the origin. That is, there is a bias error of about 1 meter. So, the bending of GPS signal paths through the troposphere increases scatter and introduces bias into the resulting differentially corrected positions. Let's move on to talk about the ionosphere.



First, let's look at the ionosphere composition. The ionosphere is composed of partially ionized gases. Ionized means that the particles have electrical charges. There are positively charged molecules and negatively charged electrons. Ionization is caused by ultraviolet sunlight, which removes electrons from neutral molecules in the atmosphere. So, high-energy sunlight comes into the atmosphere and hits a neutral (no charge) molecule and the energy from that collision strips off an electron. When this occurs the result is a negatively charged free electron and a positively charged molecule. Electric charges and magnetic fields exert forces on one another, which means that the charged particles in the ionosphere interact with the Earth's magnetic field. So, when the magnetic field is disturbed, the ionosphere can also be disturbed. The charged particles also affect the propagation of GPS signals.



Let's look at the GPS signal delays caused by the ionosphere. The magnitude of the effect, or delay, on GPS signals depends on the density of free electrons. The density of free electrons is usually referred to as the Total Electron Content or TEC. The signal path range errors vary from near zero over head to about 15 meters near the horizon. Although this is somewhat dependent on your location on Earth. We'll talk more about that later. The good news is that we have ionosphere signal delay models to remove most of the error. The most commonly used model is the broadcast model. Each GPS satellite broadcasts a global average ionosphere model down with its data stream. This is the model most commonly used by single frequency GPS systems. With dual frequency systems, the two frequencies can be combined to remove the ionosphere delay from the data, since the delay effect is frequency dependent. Let's look at an example of ionosphere induced errors.



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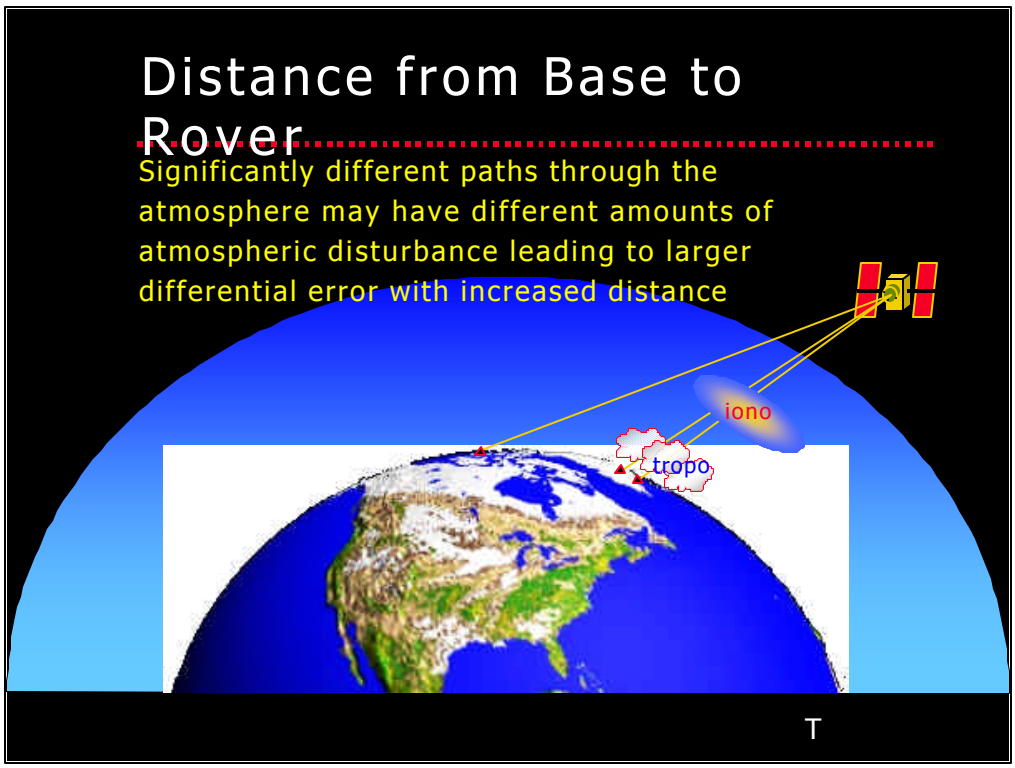
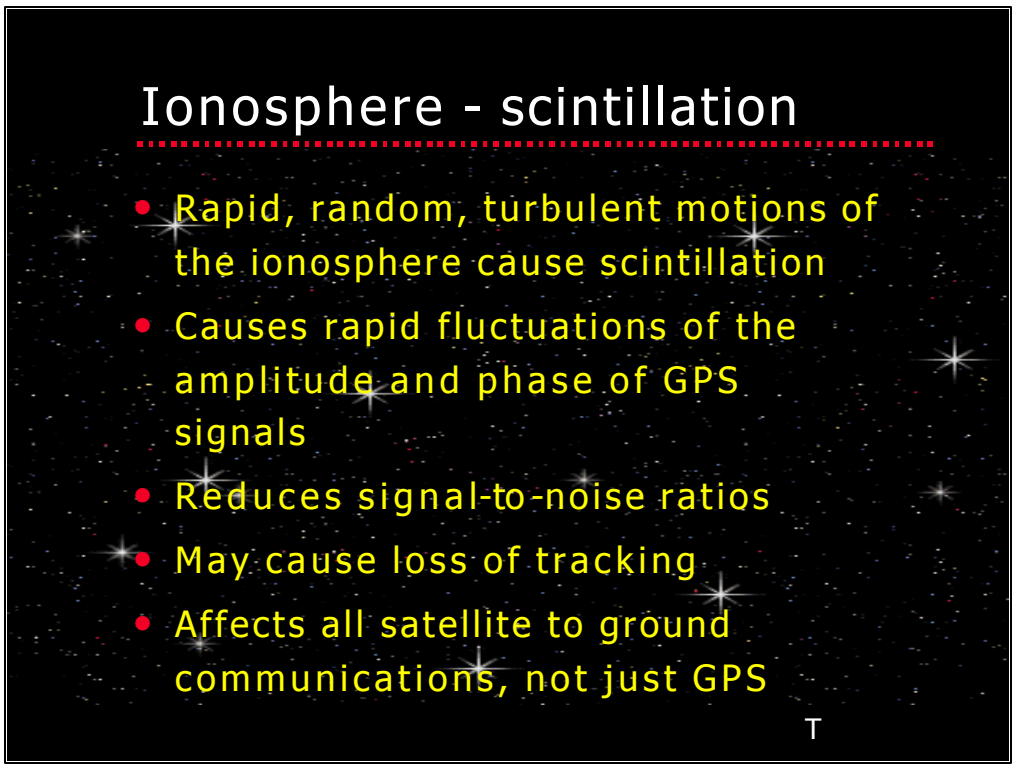
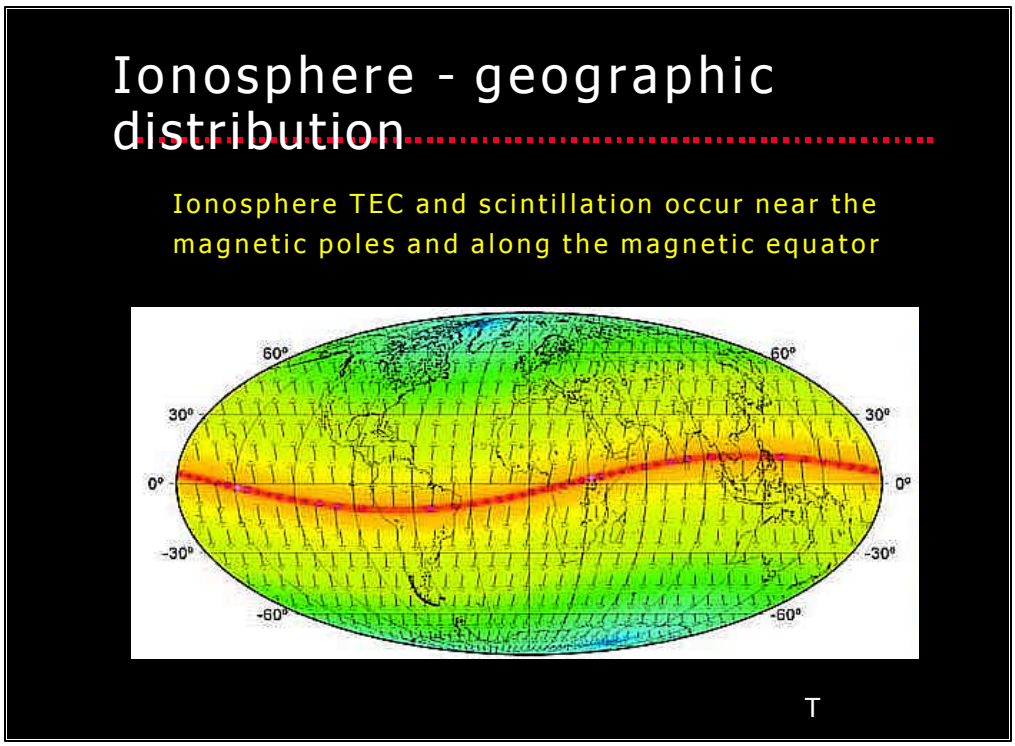


What affect does the distance between base and rover receivers have? When the satellite signals take significantly different paths through the atmosphere, they generally encounter different atmospheric conditions. As shown schematically on this slide, when your base and rover receivers are close together the signals from the satellite pass through the same atmospheric disturbances and are subjected to the same amount of delay. The process of differential correction removes this common delay from the data. This is why no model corrections need to be used with very short base to rover distances of less than 10 kilometers. When your rover is very far away from your base, then the satellite signals pass through very different atmospheric conditions. In this case, the signals arriving at the base and rover receivers have experienced different amounts of signal delay. Thus, the errors are not common between the base and rover data and do not cancel during differential correction. This is when troposphere and ionosphere models are applied to remove the errors.



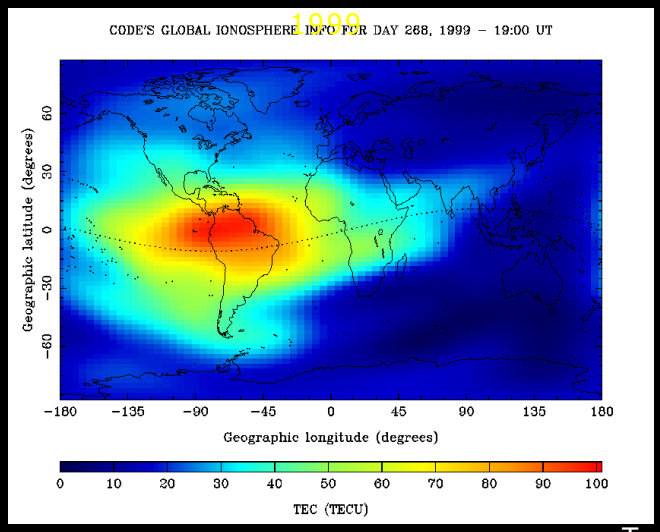
Let's talk about another effect that occurs in the ionosphere called scintillation. Lately it has become a real buzzword in the GPS community. What is scintillation? If you think of the stars in the night sky, sometimes they twinkle. The twinkling of stars in the night sky is caused by the turbulent motions the hot and cold air masses in the lower atmosphere. These motions change the amount of refraction of the starlight so that the light that reaches your eye fluctuates in amplitude and the star appears to twinkle. It is this effect that is referred to as scintillation. In the ionosphere, rapid, random, turbulent motions of the plasma (charged particles) causes scintillation. This causes rapid fluctuations of the amplitude and phase of GPS signals. It reduces the signal to noise ratios and may even cause loss of tracking in some cases. You can imagine that if you were a GPS receiver trying to see a GPS satellite signal that was twinkling, it might be hard to track that signal. It's important to note that scintillation affects all satellite to ground communications, not just GPS. The effects are frequency dependent, so different frequency systems will experience different amounts of degradation. For example, if you are using satellite based differential correction for your GPS system, you may experience loss of the differential correction signal, even though you may be receiving several GPS signals. Another important point is that scintillation effects can be localized in one portion of the sky. So, scintillation may affect just one or a few satellites, leaving you with a constellation geometry of poorer quality.



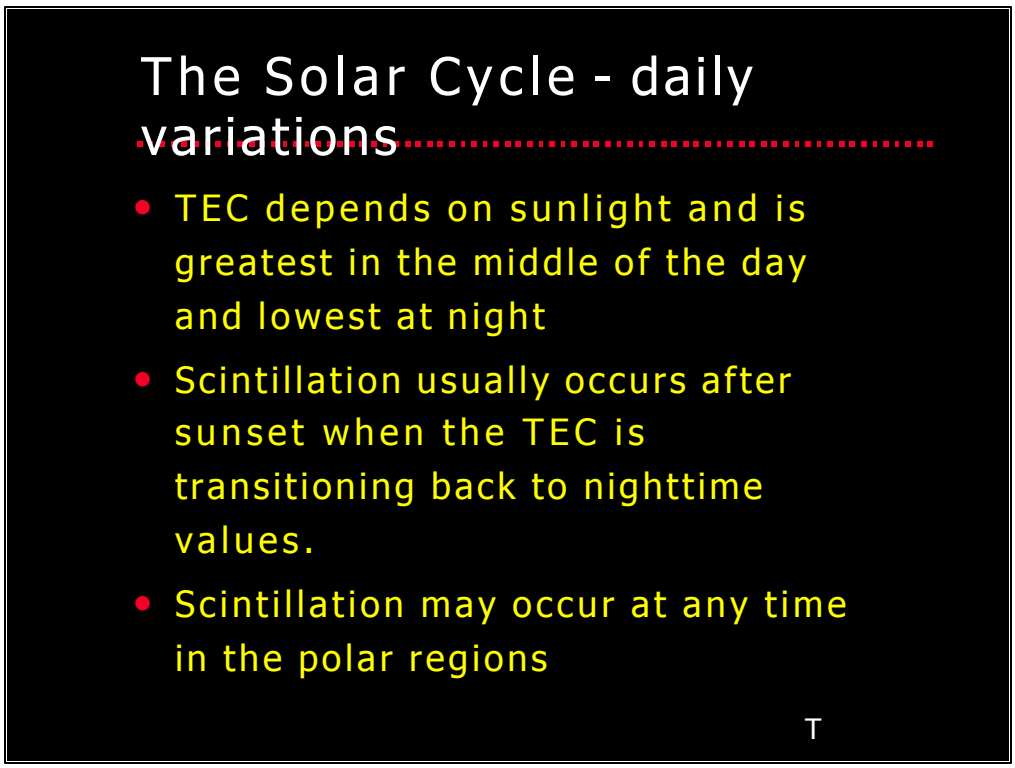
Where do these ionosphere effects occur? The geographic distribution of the ionosphere is dependent on the shape of the Earth's magnetic field. The TEC and scintillation effects are localized near the magnetic equator and the magnetic poles. This diagram shows where the magnetic field is parallel to the Earth's surface in red. Thus the red line indicates the magnetic equator. Notice that the magnetic equator is displaced from the geographic equator in two places - over South America and Southeast Asia. The magnetic poles are shown by the blue regions. In those regions the magnetic field is perpendicular to the Earth's surface. So, the places that will suffer the greatest affects of ionospheric disturbances are the areas under the magnetic equator such as South America, South Central Africa, and Southeast Asia. So, what does this TEC look like, let's take a look.

Ionosphere - TEC distribution

Global TEC distribution - September 25, 1999



Here is a map of the global distribution of Total Electron Content on September 25, 1999 at 19:00 hours UTC. The colors indicate the density of free electrons in the ionosphere in TEC UNITS, from near zero in dark blue to near 100 in red. Each TEC UNIT corresponds to about 16 centimeters of delay at the L1 GPS frequency. So we see delays near zero and up to about 16 meters over northern South America. You can see that the "blob" of TEC follows, and is generally centered around the magnetic equator. This global ionosphere TEC map is derived from a global network of 140 dual frequency GPS receivers.



Since the sun causes the TEC in the ionosphere, we need to examine how the sun's influence varies with time. The most obvious variation is daily and due to the fact that the Earth rotates on it's axis. Since the TEC depends on sunlight, it is greatest in the middle of the day and lowest at night. Scintillation usually occurs after sunset when the TEC is transitioning back to nighttime values when the electrons are recombining with their parent molecules to form neutral (non-charged) atmosphere. It is during this time of rapid cooling in the upper atmosphere that turbulence occurs and can lead to scintillation effects. In the polar regions scintillation may occur at any time. The driving forces of scintillation are slightly different in the polar regions due to the very different orientation of the magnetic field there.

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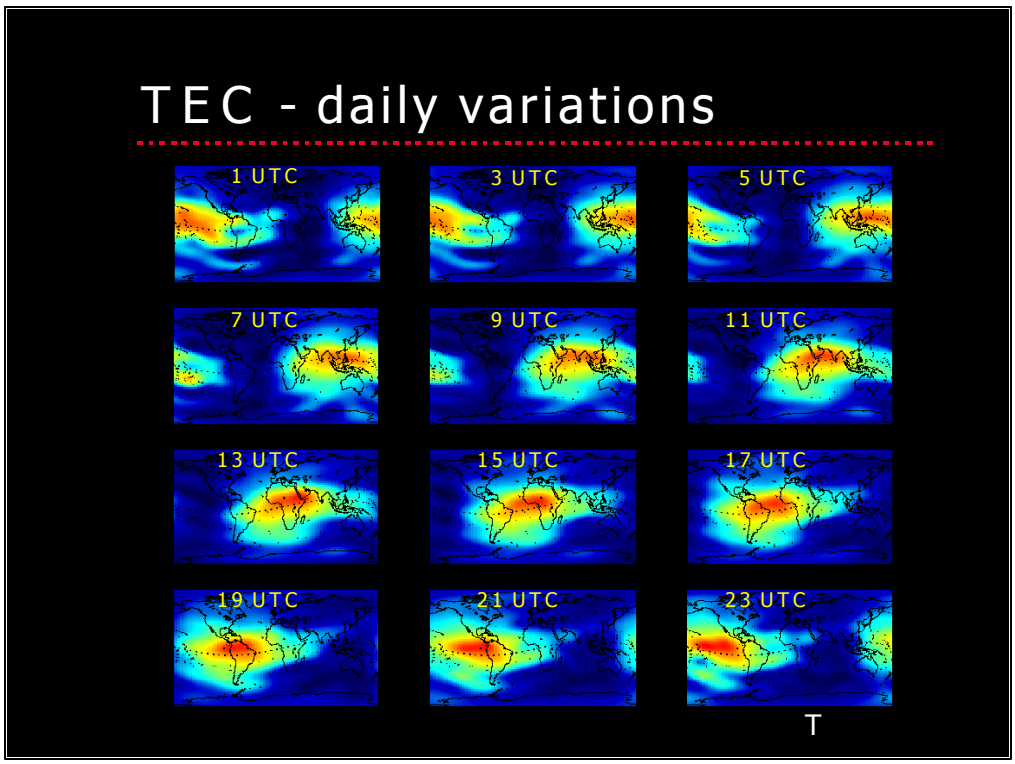
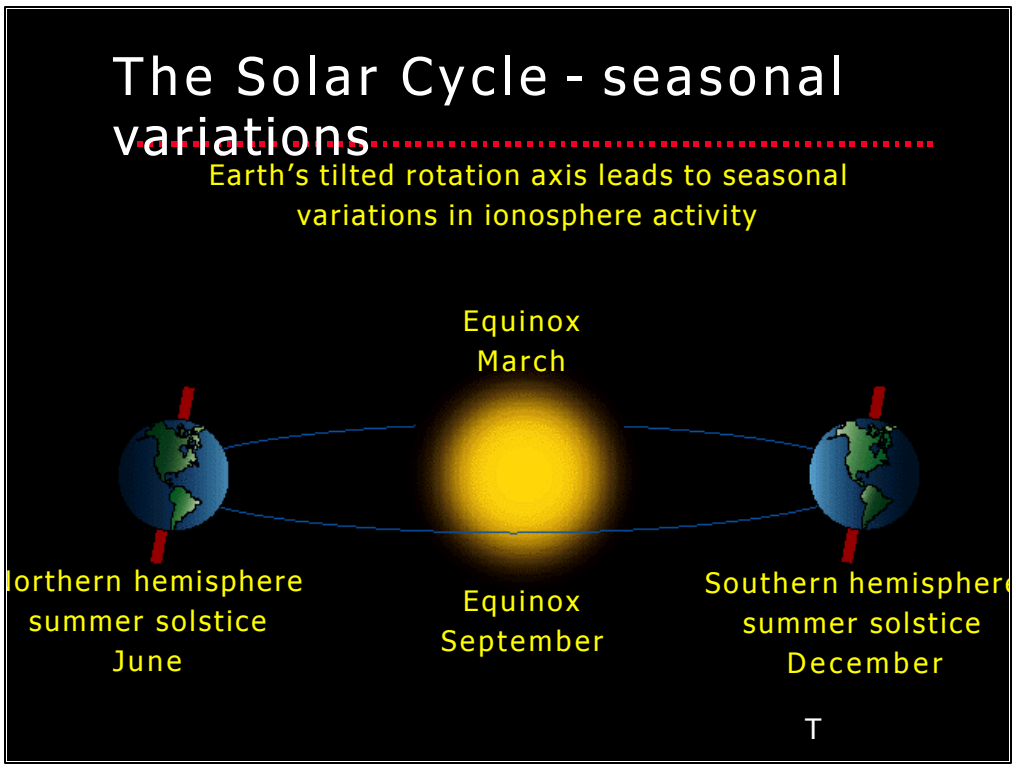
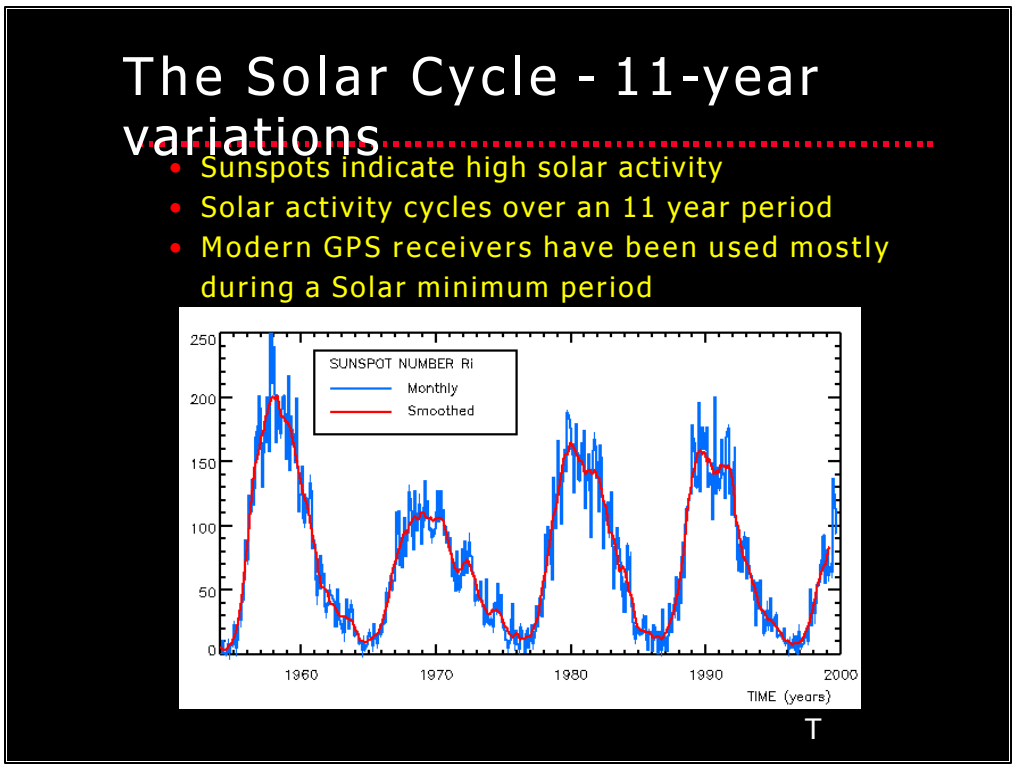


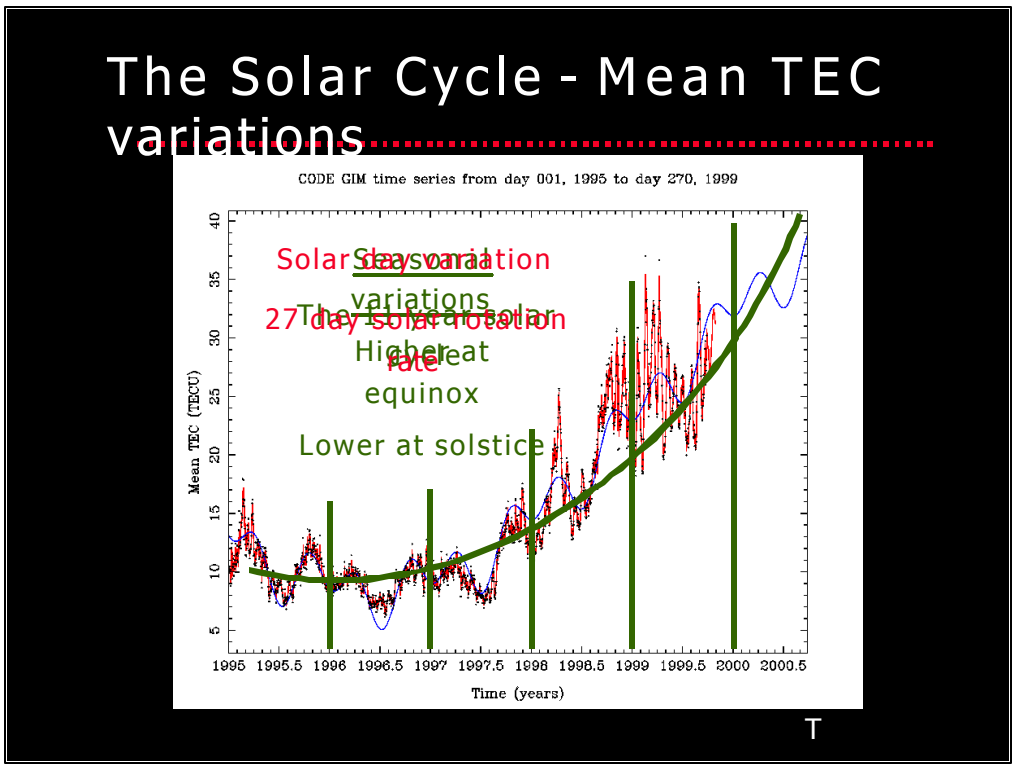
Let's look at the daily variations of TEC. This slide shows 12 global TEC maps each two hours apart. The UTC time shown on each panel corresponds to the time zone at the center of each plot (time in London). Basically, we are just looking at the Earth's rotation throughout one day. You can see that if you are in London, then at about sunrise, around 9 UTC, the TEC "blob" is just beginning to come overhead. By midday, around 14 or 15 UTC, the "blob" is right overhead, and by sunset, around 20 UTC, just the tail of the "blob" remains overhead. It is in this tail that the turbulence occurs and scintillation effects can occur. In addition to daily variation, there are also seasonal variations.



Seasonal variations in solar activity arise from the fact that the Earth's rotation axis is tilted with respect to the plane of it's orbit around the sun. This slide shows the four seasonal transitions. During the summer solstice in the northern hemisphere, in June, the sun's rays shine directly at 22.5 degrees north latitude. The summer solstice in the southern hemisphere occurs in December when the sun's rays are shining directly at 22.5 degrees south latitude. Halfway between the solstices are the equinox's in March and September. During equinox, the sun's rays are shining directly at the equator. Since the ionospheric TEC is concentrated around the equator, TEC increases during equinoxes. So, the seasonal variations induced by the Earth's tilted rotation axis also create variations in the TEC of the ionosphere. But, there are still longer variations of the suns output.

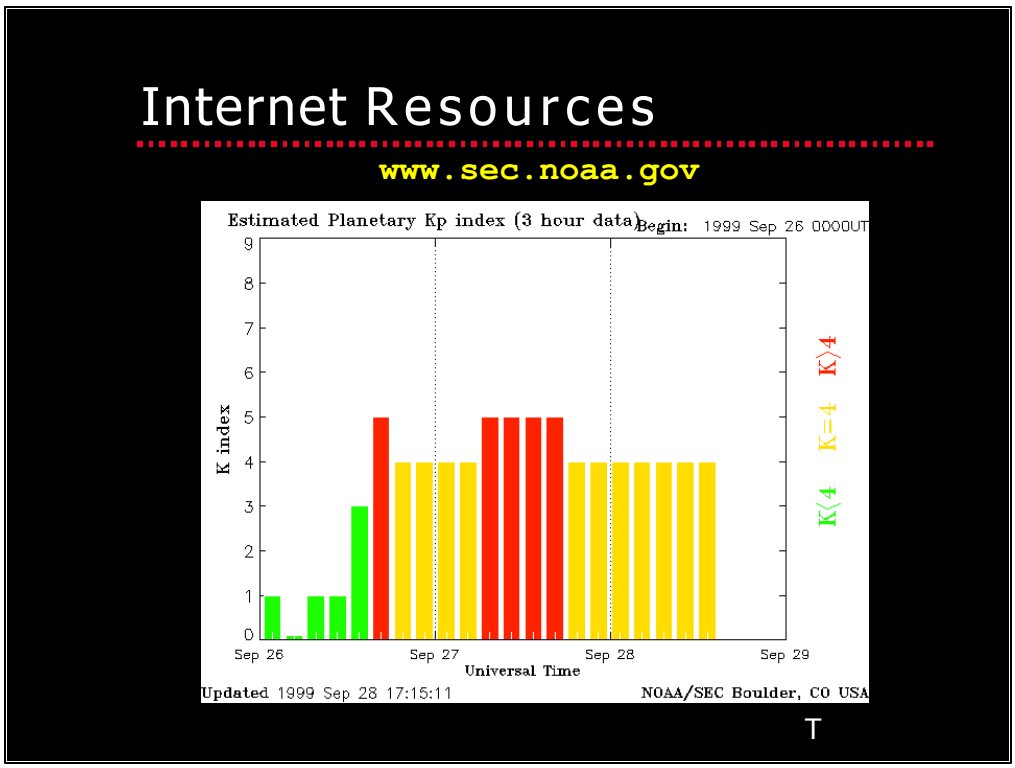


The sun's output also varies over an 11-year cycle. This variation is referred to as the solar cycle. Over two hundred years ago scientists observing the sun noticed that there were dark spots on the sun's surface and they began counting the number of spots. As the years passed, it became apparent that the number of spots varied in a somewhat regular pattern. This graph shows the number of sunspots versus time from about 1955 to the present. It's very clear that there is a regular recurrence of high and low sunspot counts. The period of these fluctuations is about 11 years. Scientists have studied the sun in great detail in recent years and have discovered that during years for which the sunspot count is high (solar max years) solar output is also high. There is a higher occurrence of high-energy bursts and emissions of high-energy radiation during those years. Since the sun directly impacts the ionosphere, as we have been learning, ionospheric activity will also increase during solar max years. Note, that the solar max periods last for 2 to 4 years in duration before the number of sunspots start to decline towards solar minimum levels. An important point here is that modern GPS receivers have only been used extensively during the most recent solar minimum period. The instruments that we use today were not ever used or studied during a solar max period. So, the upcoming solar max period will be a learning time for all of us, for you, for me and for Trimble. We will all be learning how these instruments respond and perform during the solar max conditions.

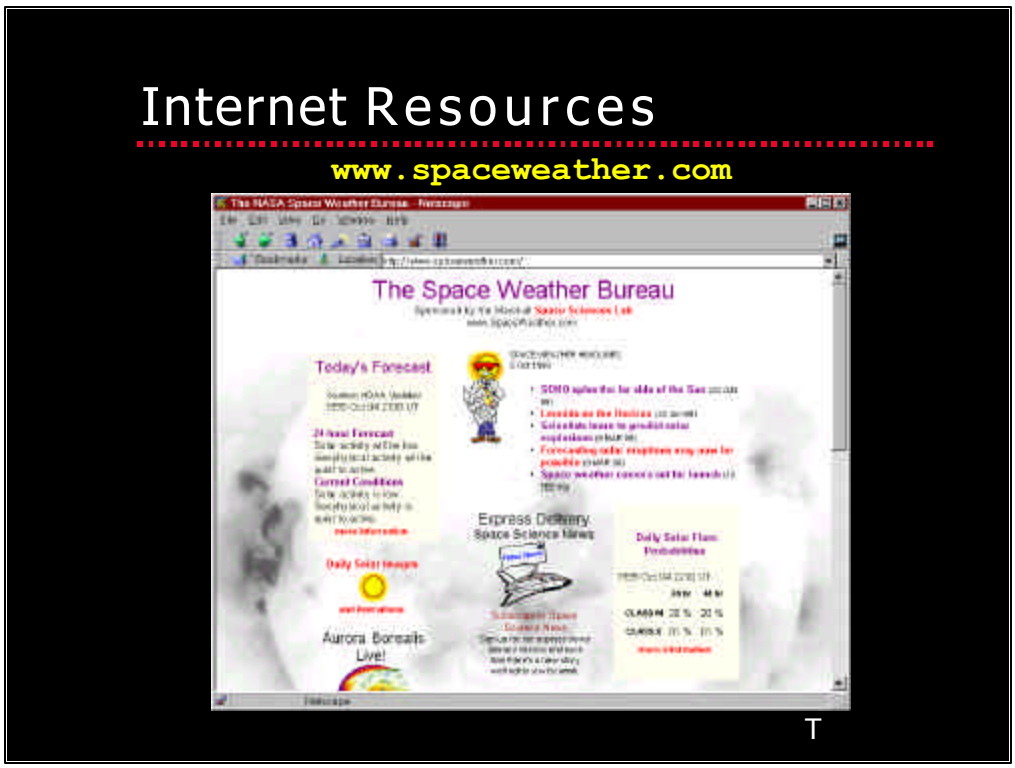


If we look at the TEC variation over time, we can see how the solar variation directly affects the ionosphere. This plot shows the global average of the TEC, derived from the global GPS network, versus time from 1995 through the present. Note that the global GPS network has only been operational since 1995 during a solar minimum period. The main trend in these data is the 11-year solar cycle. You can clearly see the solar minimum period centered around June 1996. After that time, TEC content values have been steadily increasing towards the upcoming solar maximum period. In addition to the 11-year solar cycle, you can also clearly see the seasonal variations. Each of the vertical lines added to the graph are on the one-year boundaries. Notice that within each year there are two high TEC periods and two low TEC periods, with one low period falling on the year boundary. These are the seasonal variations with the two high periods occurring at the equinoxes and the two low periods occurring at the solstices. In addition to these variations there is another one that we haven't talked about. The red curve on this plot, which shows rapid oscillations, is the solar day variation. Solar days are approximately 27 Earth days long. That is, the sun also rotates about it's own axis and makes on complete revolution about every 27 Earth days. Since sunspots are often localized on one area of the sun's surface, the radiation they emit sweeps by the Earth with every rotation, each 27 days, causing an increase in the TEC.

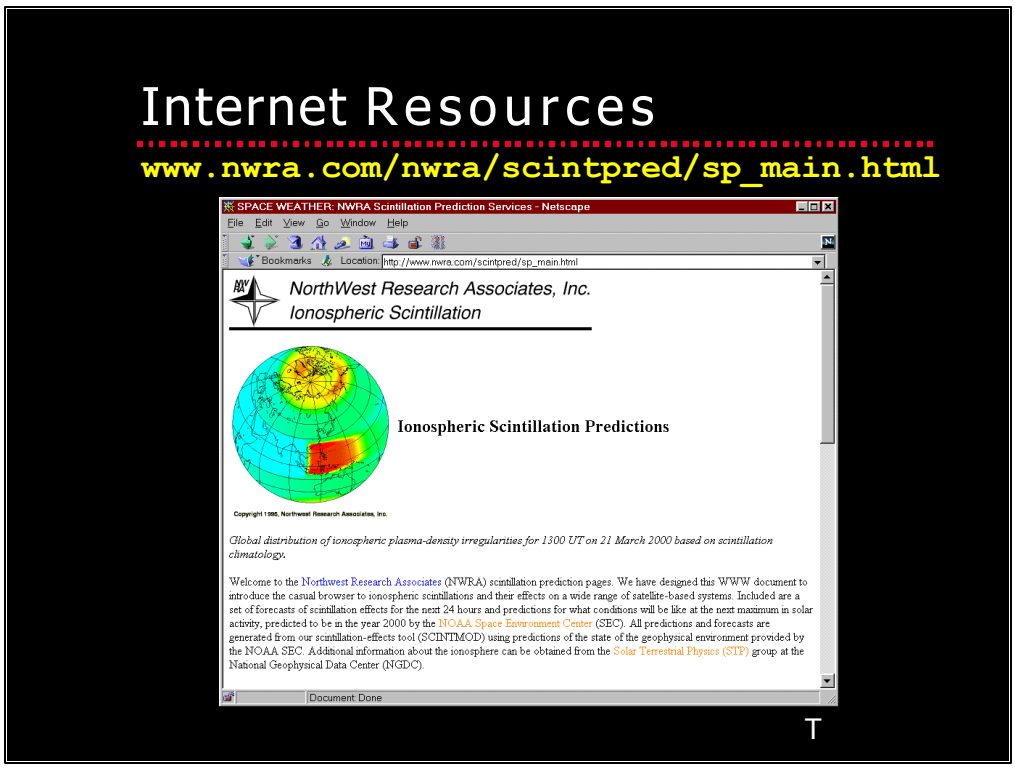
Environment Center web site has a wealth of technical information about Space Weather and atmospheric research. Right on the front page they have a link for "Today's Space Weather." They have many educational resources as well, including several papers discussing Space Weather, the ionosphere, scintillation, radio transmission issues, and navigation systems. In addition, there is a navigation page and a GPS page. On the GPS page, they present information on the activity of the magnetic field.



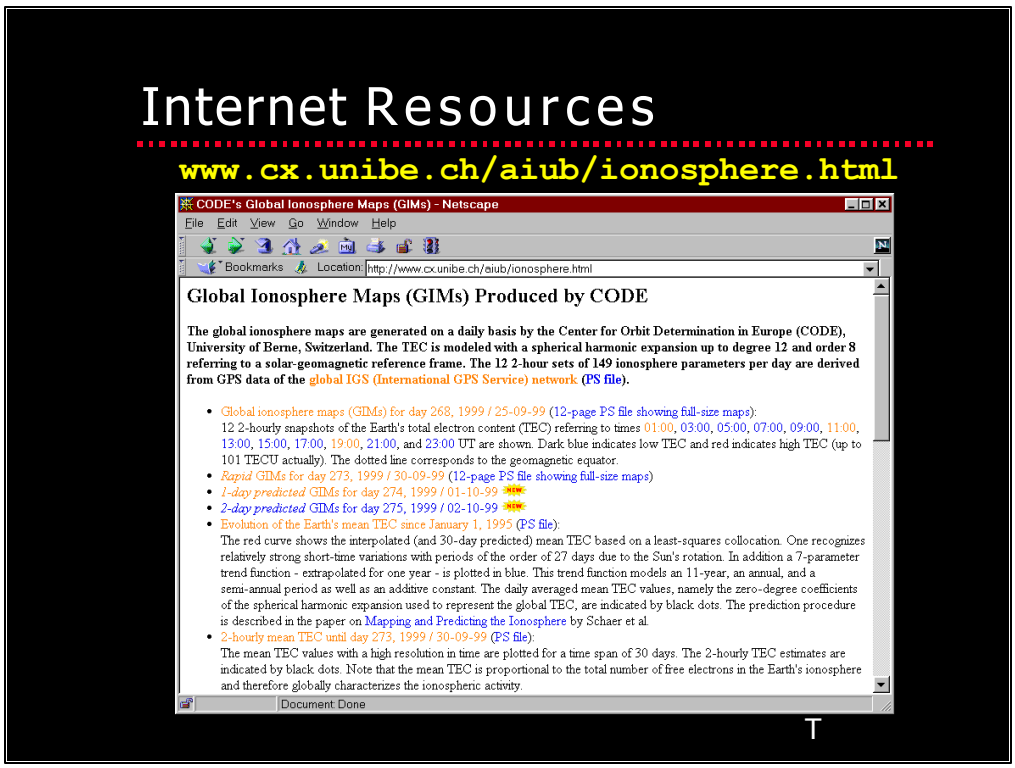
On the GPS page of the Space Environment Centers web site, they present a plot of the Kp index for three days. The Kp index measures disturbances in the Earth's magnetic field. The scale of the Kp index goes from 0 through 9, with 0 being little or no disturbance to 9, indicating severe magnetic storm conditions. Significant disturbances occur when the Kp index is above 5. Remember that disturbances in the magnetic field can cause disturbances in the ionosphere and thus affect GPS signals. These plots provide a graphical representation of the last three days of the Kp index at 3-hour time intervals. The Space Environment Center also provides a forecast of the Kp index for the next month. This can be used as a mission-planning tool for GPS field observations. If there are days that are forecast to have a Kp index above 5, you might plan not to do GPS fieldwork on those days.



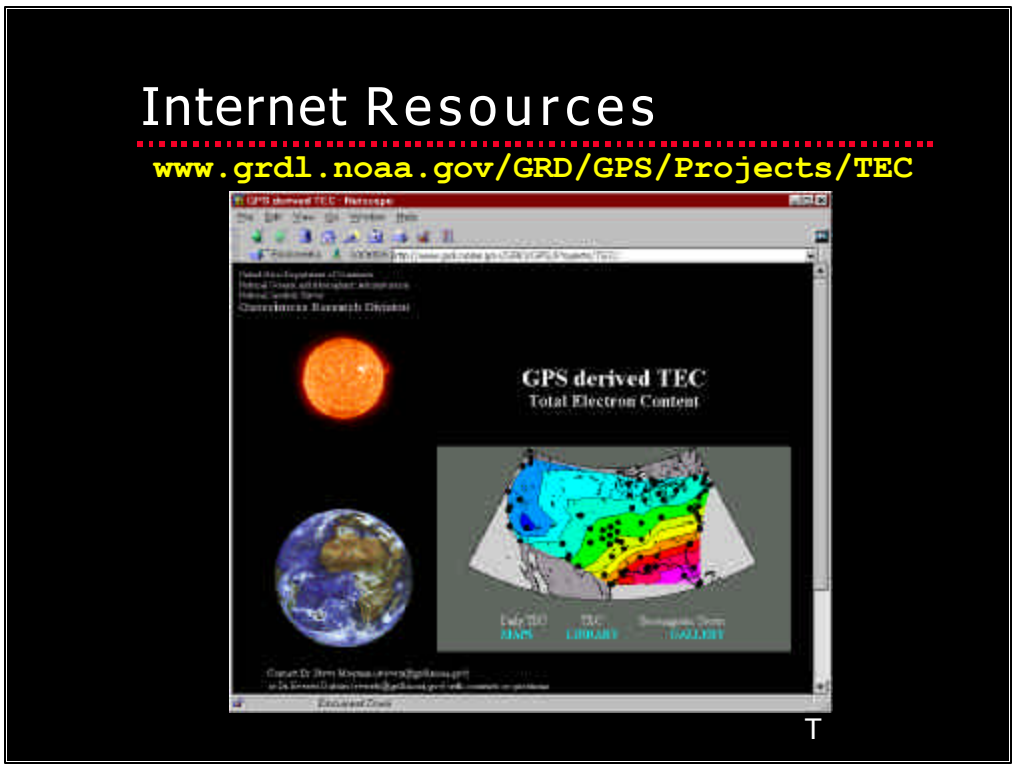
Another good source of information on Space Weather is "The Space Weather Bureau." This web site has a nicely simplified view of the information that can be found on the Space Environment Center's site. Here you can find "Today's Forecast," the "24-hour Forecast," and the "Current Conditions." A good web site for a quick look at today's Space Weather.



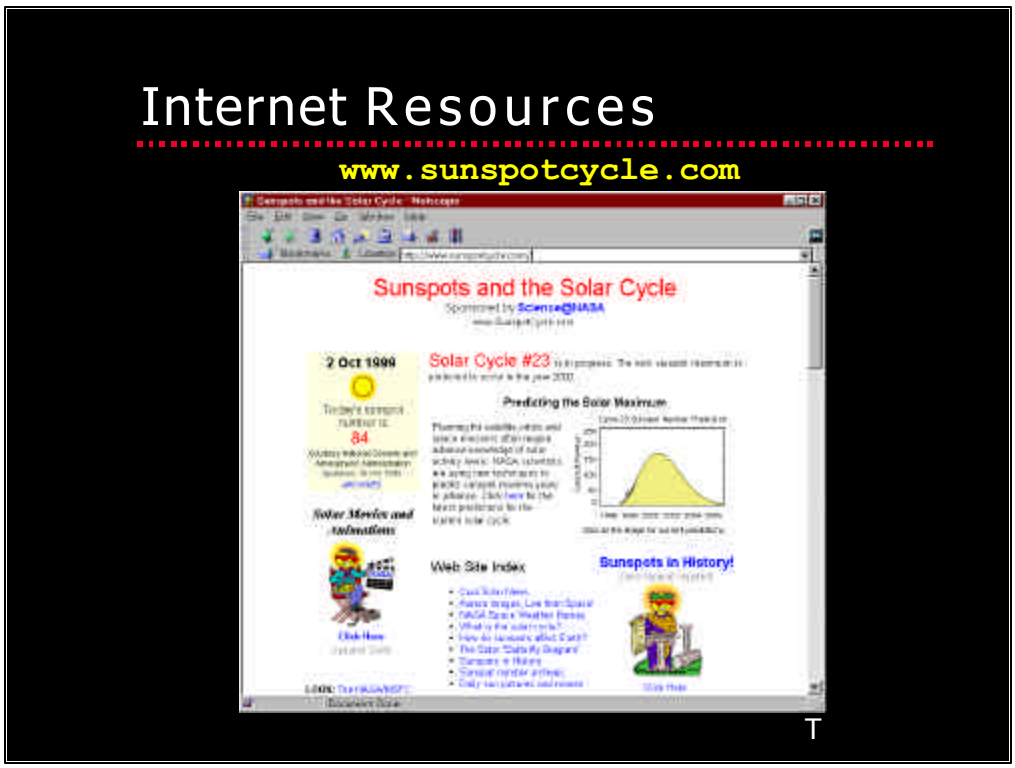
Northwest Research Associates Inc. produce this web site that describes ionospheric scintillation. They have a very informative discussion about scintillation and also describe their methods of modeling scintillation. They present 1-day ionosphere scintillation prediction maps for three regions - the Middle East, Southeast Asia, and South America. Though these prediction are not for the GPS frequencies, they are representative of where and to what extent scintillation occurs. Northwest Research Associates can also provide customized scintillation models as a consulting service.



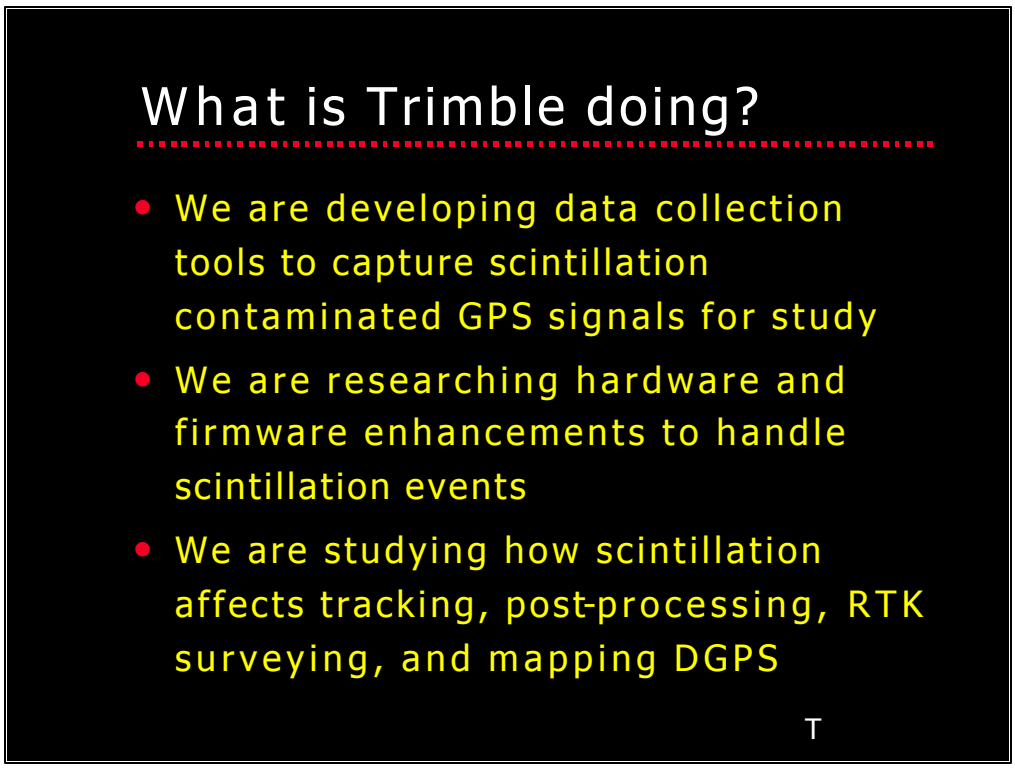
The Center for Orbit Determination in Europe produces the global ionosphere maps of TEC that I have presented in this talk. Using this web site, you can view the daily map, as well as predicted maps for the next two days. They also have a couple of graphs of the history of global TEC. All the TEC information is generated from the global network of dual frequency GPS receivers (140 stations).



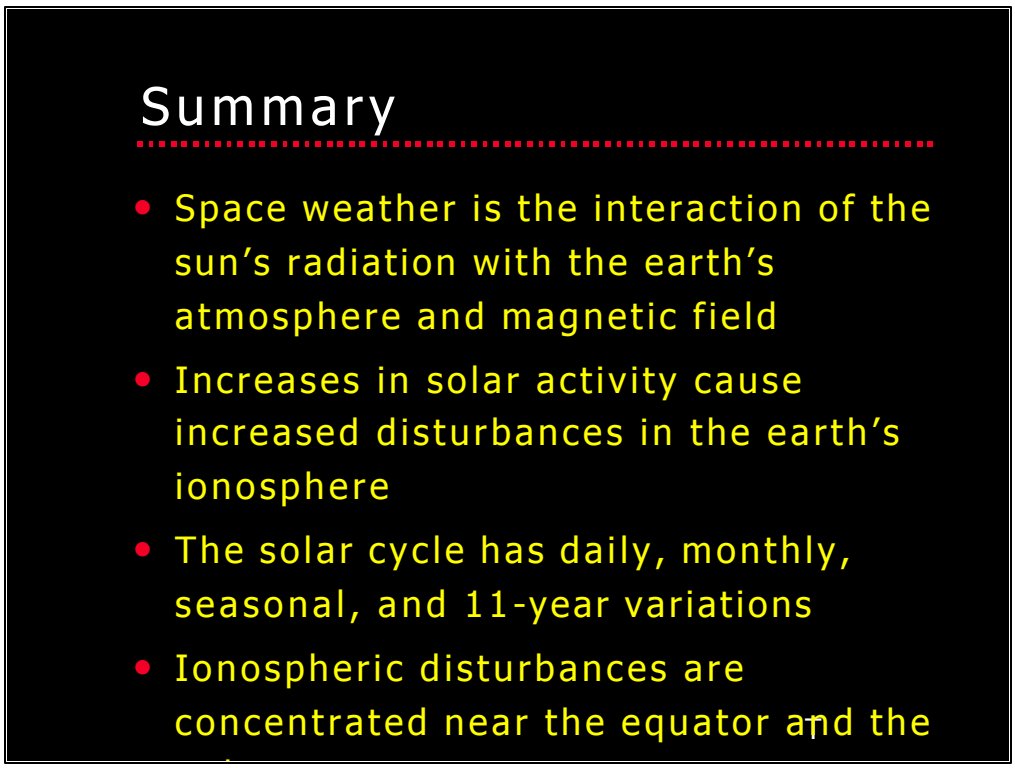
If you are working in the continental U. S., the Geosciences Research Division of the National Oceanographic and Atmospheric Administration produces an animated daily map of TEC. In addition to the daily map, this site also has a history of maps. This allows you to compare different days or times of the year to get a feel for when the TEC is changing. You might ask what use are these maps? While they are not useful for prediction, since they are only available after the fact, they may be useful for debugging noisy data sets. If you have a noisy or problematic data set and you have already ruled out all the possible causes that you can think of, you might then take a look at the TEC maps. By comparing the day and time of your noisy data to the maps at that time, you might find that the TEC was particularly high and that might be the cause of the noisy data.



The Sunspot Cycle web site is a great starting place for information about the solar cycle. They display the current daily sunspot number and have information on everything you ever wanted to know about the sun. They present a little graph of the current sunspot cycle right on the front page. Notice that the width of the peak of this cycle is predicted to be 2 to 3 years long. So, issues related to the solar max period will be with us for the next 2 to 3 years.



What is Trimble doing? We are developing special data collection tools to capture scintillation contaminated GPS signals. We will use this data to study how our receivers behave under these difficult conditions. We are researching enhancements to our receivers and firmware that will help to handle scintillation events. And, we are studying how scintillation affects tracking, post-processing, RTK surveying, and mapping DGPS.



Let's look at a summary of what we have learned today.

Summary

- Ionosphere scintillation occurs mostly after sunset in the equatorial regions, but may occur anytime near the poles
- Models and dual frequency observations help to remove atmospheric delays
- The Internet is a valuable source of information about the solar cycle, ionosphere, and space weather

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What can YOU do?

- Change the way you work, by...
- Maintaining an awareness of the solar cycle
- Knowing when and where you may encounter increased noise or scintillation
- Using the forecast Kp index as a mission planning tool

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